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RELIABILITY ASSESSMENT OF QUICK CLOSING VALVES IN HYDROELETRIC POWER PLANT

Abstract

The assessment of existing components of power producing facilities is based on probabilistic methods of the theory of reliability provided in Eurocodes and ISO standards. An example of quick-closing valves in a selected hydroelectric power plant indicates the assessment of reliability and the prediction of the remaining working life of a structural component for the considered model of corrosion.

Keywords

Probabilistic assessment, remaining working life, quick-closing valves, reliability index.

1 INTRODUCTION

Probabilistic methods may be effectively applied for the assessment of reliability and remaining working life of existing structures. Presently two new international documents ISO 13822 [9] for the basis of the assessment of existing structures, and ISO 13823 [10] for durability design are based apart from the partial factor method on probabilistic methods. These documents were developed considering the probabilistic principles of the international standard ISO 2394 [8], the Eurocode EN 1990 [3] and fib Bulletin 34 [7].

The paper describes probabilistic procedures for the durability assessment of existing power-producing facilities and their application for the assessment of the remaining working life of the quick-closing valves of the hydroelectric power plant located in the river Vltava in the South Bohemia.

2 BASIC RELIABILITY REQUIREMENTS

The reliability requirements for existing structures as well as for new ones may be expressed in terms of the failure probability P_f or reliability index β. The relationship between the both reliability indicators may be expressed as

$$P_f = \Phi(-\beta) \tag{1}$$

where Φ(.) denotes the standardized normal distribution function. The following reliability condition is required

$$P_f \le P_{ft} \text{ or } \beta \ge \beta_t \tag{2}$$

where P_{ft} and β_t are the target values of the failure probability and reliability index.

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The target reliability level which should be used for the verification of existing structures may be based on an optimisation analysis and calibrations taking into account the concept of the minimum expected costs and social risks. The recommended values of the target reliability index β_t for the verification of various limit states given in ISO 13822 [9] are illustrated in Tab.1.

It should be noted that more detailed target reliability indices depending on the consequences of failure and the relative costs of safe design are provided in ISO 2394 [8].

Tab. 1: Indicative target reliabilities for existing structures.

Limit states	Target reliability index β_t
Serviceability – irreversible	1.5
Ultimate with failure consequences	
– very low	2.3
– low	3.1
– medium	3.8
– high	4.3

EN 1990 (2002) provides principles of reliability differentiation in the informative Annex B. Three basic reliability classes RC1 to RC3 are recommended there and target values of reliability indices β_t proposed including examples of construction works. Presently, hydrotechnical construction works are not included in the scope of current generation of Eurocodes. Thus, supplementary provisions have to be nationally developed, see e.g. [1].

Reliability differentiation of hydrotechnical construction works is illustrated in Tab. 2 as recommended in the recently developed National Annex to CSN EN 1990 [2] of the Czech Republic.

Tab. 2: Reliability differentiation of hydrotechnical structures according to CSN EN 1990 [2].

Reliability class	Examples of construction works
RC3	Dam, weir higher than 5 m, main conduit of potable water to town agglomeration
RC2	Sewage disposal plant, accumulating pumping plant, water reservoir, aqueduct, hydro-electric power station, weir high up to 5 m, fire reservoir
RC1	Swimming pool, melioration structure

The partial factors for hydrostatic and hydrodynamic pressures, permanent and variable actions recommended in the recently developed CSN 75 6303 [1] for the reliability classes RC1 to RC3 are given in Tab. 3.

Tab. 3: Partial factors for actions.

Type of action	CSN 75 6303 [1]		
	RC1	RC2	RC3
Hydrostatic pressure	1.0	1.1	1.2
Hydrodynamic pressure	1.2	1.3	1.4
Permanent action	1.2	1.35	1.4
Variable action	1.35	1.5	1.65

The application of probabilistic methods for the specification of the working life of an existing structure is illustrated in Fig. 1. It is assumed that the assessment (inspection) of an existing component of a power producing facility is performed in a time t_{pr} from the beginning of the structure completion. In case that the time-dependent resistance $R(t)$ of a component and load effects $E(t)$ are known, the remaining working life of the component may be specified.

For estimation of the residual working life t_{res} of the component, the following expression is given as

$$P_f(t_{res}) = P\{R(t_{res}) - E(t_{res}) < 0\} < P_{target} \tag{3}$$

facilitating the decision about its repair or replacing.

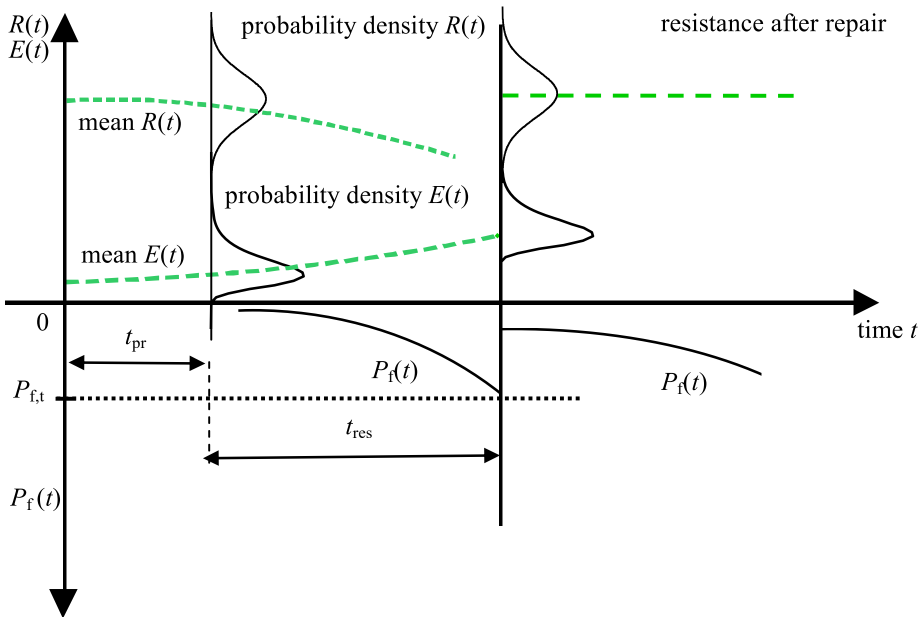

Fig. 1: Probabilistic assessment of remaining working life.

3 VERIFICATION OF COMPONENTS

The general requirements for the assessment of structural serviceability are applied for the reliability analysis of many years safely running quick-closing steel valves in a selected hydroelectric power plant operating about 50 years.

3.1 Analysis based on the partial safety factor method

Firstly, the partial factor method provided in EN 1990 [3], basis for assessment of existing structures ISO 13822 [9] and EN 1993-1-1 [4] for design of steel structures are applied for the verification of a selected energetic component.

A cover plate of a thickness of 0.018 m is continuously supported with stiffeners 0.75 m spaced. Water pressure is composed of hydrostatic and hydrodynamic components given as

$$q = q_{hs} + q_{hd} = \rho g h + \rho Q v / A \tag{4}$$

where ρ is the water density, h is the depth, Q is the flow rate, v is the water speed, A is the area of the cover plate and g acceleration of gravity.

The reliability of the cover plate of the quick-closing valve is based on the partial factor method and the basic condition $M_{Rd} > M_{Ed}$ between the design value of bending moments for resistance and the effects of actions. The reliability of the component is verified with respect to the ultimate limit state given as

$$M_{Rd} = \gamma_u b d^2 f_{yk} / (4\gamma_M) \tag{5}$$

where the characteristic value of steel yield strength is f_{yk} = 235 MPa, partial factor of steel γ_M = 1.15 and the coefficient of model uncertainties γ_u = 0.85 according to CSN 75 6303 [1].

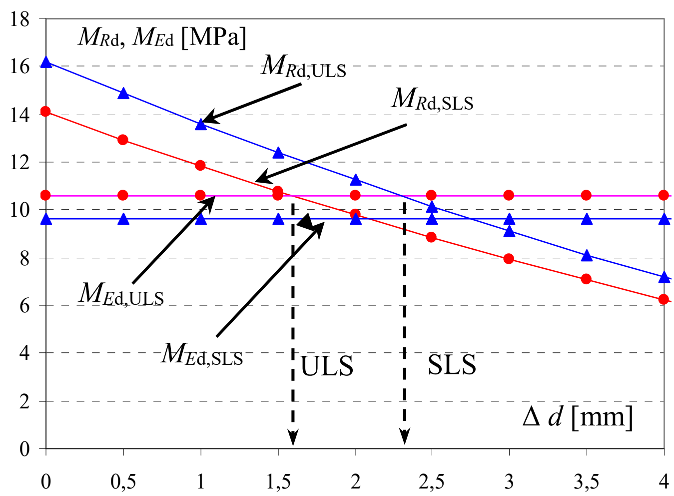

Fig.2: Progressive loss of the component resistance and serviceability, expressed in moments M_E, M_R [MPa], with the decrease of the material thickness Δ d [mm].

The action effect is evaluated for the maximum water pressure and for the span L of the cover plate

$$M_{Ed} = \delta(\gamma_{Qhs} q_{hs,k} + \gamma_{Qhd} q_{hd,k}) L^2 / 12 \tag{6}$$

where the values of partial factor for the hydrostatic pressure γ_{Qhs} = 1.1 and for the hydrodynamic pressure γ_{Qhd} = 1.2 are considered according to Tab. 3 based on CSN 75 6303 [1] where the dynamic amplification factor δ = 1.3 is also provided.

The reliability of the component is also verified with respect to the serviceability limit state given as

$$E_d \leq C_d \tag{7}$$

where E_d is the design value of the effects of actions specified in the serviceability criterion, determined on the basis of the relevant combination C_d represents a limiting deformation.

Decreasing the reliability of the cover plate with the decrement Δd of the plate thickness is illustrated in Fig. 2 for both the ultimate (ULS) and serviceability (SLS) limit states.

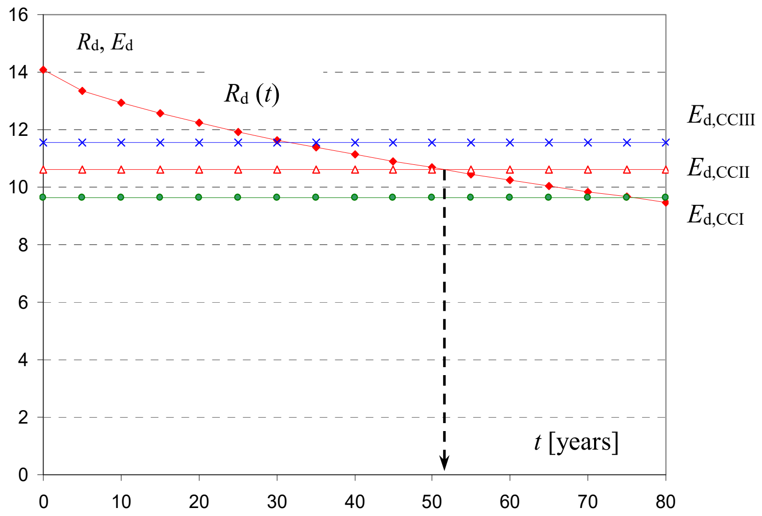

Fig. 3: Reliability of the structural member classes CC1 to CC3 in time

Decreasing time-dependent reliability of a steel cover plate categorized to three reliability classes CC1 to CC3 is illustrated in Fig. 3. In case that the partial factor method is applied for the verification of an existing structural member in class CC2, it is shown that its bearing capacity is exhausted after about 53 years and some measures are needed (e.g. strengthening, replacement).

3.2 Application of probabilistic methods

The probabilistic methods of the theory of structural reliability are applied for the specification of the reliability index β and the failure probability P_f.

The inspection of the quick-closing valves of the hydro-electric power plant revealed the deterioration of the components including their steel cover plates as illustrated in Fig. 4.

Fig. 4: Deterioration of a steel cover plate.

It is assumed that the time-dependent depth of corrosion $d_{\mathrm{corr}}(t)$ in the steel cover plate may be estimated on the basis of the relationship

$$d_{\mathrm{corr}}(t) = B\, t^{C} \tag{8}$$

where B and C are the parameters of analytical model, which are considered for the parameter B in the range from 0.03 to 0.13 mm and for the parameter C from 0.6 to 0.7 mm, see e.g. [11]. It might be assumed here for non-uniform corrosion

$$B = 0.06 \text{ mm, and } C = 0.7 \text{ mm} \tag{9}$$

based on the results of the inspection of the actual state of steel quick-closing valves. Pitting corrosion with pits up to 2 mm is shown in Fig. 5.

Fig. 5: Pitting corrosion of a steel plate.

It is considered that the steel cover plate of quick-closing valves having age of about 50 years is gradually deteriorating due to non-uniform corrosion with the average one-side decrease up to 1 mm and about 30 % probability of simultaneous weakening at the opposite side of the cover plate. Therefore, the model of corrosion introduced in equation (8) considering parameters in equation (9) leads after 50 years to the actual average depth of corrosion of 1.3 mm.

The ultimate limit state is expressed as the difference $\Delta M(t)$ of the time-dependent resistance moment $M_R(t)$ and the bending moment M_E due to the water pressure q

$$\Delta M\left(t\right) = x_R b\left(d - 1{,}3 d_{corr}\left(t\right)\right)^2 f_y / 4 - \delta q L^2 / 12 \tag{10}$$

The theoretical models of all variables are listed in Tab. 4. Some of the basic variables entering expression (10) are assumed to be deterministic values denoted DET (a steel cover plate of a span L, width b, the parameter of corrosion B and the dynamic factor δ) while the others are considered as random variables having normal (N) or lognormal (LN) distributions.

The reliability of the steel cover plate decreases in time due to the corrosion leading to reduction of its thickness $d_{\mathrm{corr}}(t)$. The value of the target reliability index $\beta(80) = \beta_{\mathrm{t}} = 3.7$ for the considered 80-year working life of the cover plate is specified on the basis of the required reliability index for a reference period of one year $\beta(1) = 4.7$ given by expression in Annex C of CSN EN 1990 [2] given as

$$\Phi(\beta_n) = \left[\Phi(\beta_1)\right]^n \tag{11}$$

Tab. 4: Probabilistic models of basic variables.

Basic variable	Symbol	Distr.	Mean m	C.V. V
Yield strength [MPa]	f_y	LN	280	0.08
Plate span [m] Plate thickness [m] Plate width [m]	L d b	DET N DET	0.75 0.018 1	- 0.03 -
Parameter B [mm] Parameter C	B C	N DET	0.06 0.7	0.10 -
Water pressure [kN/m^2]	q	N	157.6	0.1
Dynamic factor	δ	DET	1.3	-
Resistance uncertainty	ξ_R	DET	0.85	-
Yield strength [MPa]	f_y	LN	280	0.08

The probabilistic reliability assessment of the steel cover plate is based on the authors´ own Mathcad-based software tool.

The initial reliability of the cover plate non-affected by corrosion (the reliability index $\beta = 5.2$ corresponding to failure probability $P_F = 9.4 \times 10^{-8}$) satisfies the target reliability level for the assumed reference period of 80 years ($\beta_t = 3.7$). For one-side corrosion of 1 mm and a cover plate 53 years old (current state), the reliability index decreases to $\beta = 4$ (failure probability $P_F = 3.6 \times 10^{-5}$), see Fig. 6.

It appears that the working life of the cover plate may be estimated to approximately 70 years when the reliability index β(t) decreases to 3.7. Thus, the residual working life of the cover plate is considered to be about 20 years.

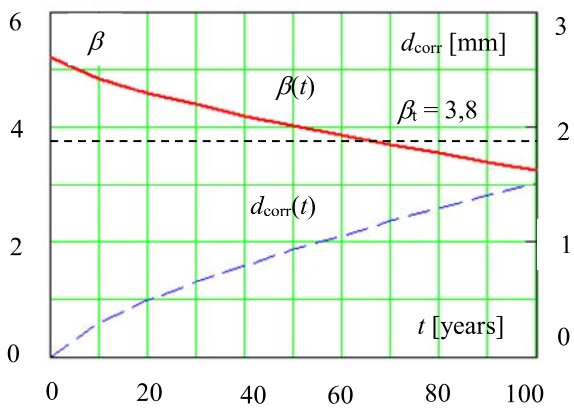

Fig. 6: Time-dependent reliability index β(t) and one-side corrosion depth $d_{corr}(t)$.

In case that a more effective protection level of a cover-plate is provided (currently planned) then a lower rate of corrosion may be considered (e.g. parameter B = 0.6 only, case 1 illustrated in Fig. 7). A new estimation of the residual working life leads to the residual working life extended from 70 to 90 years.

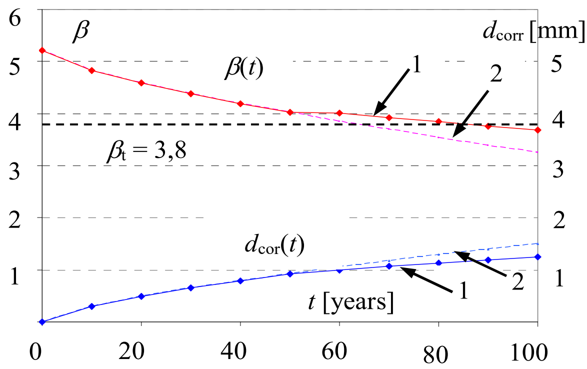

Fig. 7: Time-dependent reliability index $\beta(t)$ and one-side corrosion depth $d_{corr}(t)$ for the considered increased maintenance level (case 1). Case 2 indicates a common level of maintenance.

4 CONCLUSIONS

It is shown that the application of the partial factor method for the assessment of existing structures may lead in some cases to conservative estimations. The probabilistic assessment of existing structures facilitates to effectively estimate remaining working life of structures and to plan their maintenance and required economic resources. The assessment of the quick-closing valves has shown that their remaining life-time is about additional 20 years provided their regular maintenance. Protective layers of steel components should be renovated and regularly inspected. When the reliability index decreased below the target reliability index 3.7 (estimated to 20 years), a new reliability assessment of cover plates should be made on the basis of updated material characteristics.

ACKNOWLEDGMENT

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